



This report was prepared by Philip J. Schmitt, Assistant to the Director, Federal Bureau of Investigation, United States Department of Justice, and is being submitted to the Attorney General for his review.

After consideration of the report, it was found that the information contained therein is of such a nature as to require the attention of the United States Government. It is recommended that the report be referred to the appropriate departments and agencies for their consideration and action. It is further recommended that the report be made available to the public in order that they may be fully informed of the facts and circumstances involved.

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Assistant to the Director  
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FOR THE COMMISSIONER

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# REPORT DOCUMENTATION PAGE

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Conventional three-potential attenuators were developed in the 1950s and had accuracies limited to 1.5% transmission and 1% reflection. However, the Collins Laboratory had at least ten years experience with the design and construction of attenuators which employed either a half-wave or a quarter-wave transmission line in conjunction with two shorted pistons. The purpose of the current effort was to use the same concept using extremely high quality optical fiber. Longman prism attenuators provide attenuated signals and an experimental setup designed to provide accurate measurements for high reflection. Also, to determine the feasibility of using a three-stage potential attenuator with lower losses in the 100 to 1000 nm range. The design would be used to calibrate experimental signals and the transmission of visible signals. The experimental results indicated that the attenuator could only provide uncertainties of 1 to 2 percent. The photometric accuracy was not tested with visible sources. Because the attenuator was made in a standard practical construction of a two-potential and a half-wave range with a single technique, it was used to calibrate visible signals over a wavelength range of 400 to 1000 nm. It was found that the accuracy of the three-stage attenuator was 1 to 2 percent.

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# CONTENTS

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION	1
2.0 EXPERIMENTAL ARRANGEMENT	3
2.1 ATTENUATOR DESIGN	3
2.2 ALIGNMENT OF THE ATTENUATOR	5
2.3 EXPERIMENTAL LAYOUT	7
3.0 DATA INTERPRETATION AND EXPERIMENTAL RESULTS	11
3.1 MEASUREMENT RESULTS	11
3.2 EXPERIMENTAL ERROR	18
3.2.1 Measurement Error	18
3.2.2 Systematic Error	18
4.0 CONCLUSIONS	19
REFERENCES	20
APPENDICES	21
A. RAW DATA COLLECTED	21
B. REDUCED DATA	21

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## FIGURES

<u>Figure</u>	<u>Page</u>
1. Three-stage polarizer attenuator.	3
2. Attenuation alignment procedures.	6
3. Schematic of experimental layout.	8
4. Basic setup of utility box.	9
5. Ray diagram of photometer, filter wheel assembly, and PMT	10
6. Experimental and theoretical transmittance versus the prism rotation angle.	12
7. Measured signal versus theoretical transmittance for data in the vicinity of 90 and 270 deg.	13
8. Measured signal versus theoretical transmittance for the entire data set.	14
9. Data plot of the transmittance versus the prism rotation angle.	15
10. Ratio of the experimental transmittance to the theoretical transmittance versus the prism rotation angle.	17

## 1.0 INTRODUCTION

Conventional polarizer attenuators have been used since at least the 1920s. The transmittance of the two-stage polarizer attenuator, where one polarizer is fixed and the other one is rotated, is known as Malus' law:

$$T(\delta) / T(0) = (\cos \delta)^2$$

where  $T(\delta)$  is the transmittance of the two polarizers and  $\delta$  is the angle enclosed by the principal transmittance axes. This device was unreliable if the source was partially polarized or the sensitivity of the detectors varied with the angle of polarization (Ref. 1). Dowell developed the three-stage polarizer attenuator which overcame the defects in the two-stage attenuator (Ref. 2). In Dowell's method the first and last polarizers were stationary with their optic axes parallel and the middle polarizer was rotated. The three-stage polarizer attenuator transmitted an intensity governed by a  $\cos^4$  relationship.

$$T(\delta) / T(0) = (\cos \delta)^4$$

To obtain accurate measurements, the extinction ratios of the polarizers and the birefringence of the middle polarizer must be known and accounted for when the attenuator is calibrated. In general, the conventional three-polarizer attenuators utilizing film polarizers were limited to 0.001 transmittance units (Ref. 1).

Several different types of polarizers have been used in the three-stage attenuators. Bennett used sheet Polaroid mounted between distortionless glass plates and determined photometric linearity to better than 0.1 percent (Ref. 3). Mielenz and Eckert discussed systematic errors due to imperfections in sheet polarizers, setting and alignment errors, and incident beam incidence angle and polarization. They concluded that the accuracy of three-polarizer film attenuators is limited to 0.001 transmittance unit largely because of the unknown birefringence of the middle polarizer. Instead they employed either a half-wave or a quarter-wave retardation plate with a precisely known birefringence and two sheet polarizers and obtained at least 10 times more accuracy than the conventional three-polarizer attenuators (Ref. 1).

Polarization prisms would also avoid the birefringence problem. Mielenz and Eckert did not pursue the use of prisms because of potentially serious systematic errors caused by their small field angles and because the accurate measurement of the high extinction ratios of good polarizers was difficult (Ref. 1). Bennett tested, but did not use, a good Glan-Thompson prism that deviated the beam by less than 1 min of arc

and was a high schlieren quality calcite, because the intensity variation was not symmetric in the four quadrants. He suggested that a prism-type polarizer with adequate performance would have the advantage of a wider, more useful spectral range than was possible with sheet polarizers (Ref. 3).

The current work was based on the same concept and used specially selected high quality optical Glan-Thompson prisms, extremely precise automated stages, and a combination of optical density filters with a lock-in amplifier, to obtain accurate measurements and to determine the feasibility of using a three-stage polarizer attenuator with laser beams in and near the visible range. This device should be effective for independently calibrating experimental signals and transmittance of neutral density filters over a wavelength range from 350 to 2500 nm and over an optical density range of nine orders of magnitude.

## 2.0 EXPERIMENTAL ARRANGEMENT

### 2.1 ATTENUATOR DESIGN

The three-stage attenuator was comprised of specially selected high quality optical Glan-Thompson prisms manufactured by Karl Lambrecht Corporation (MGT25E10-90), Chicago, Illinois. The calcite prisms are glued at the interface. The optical glue limited the capability of the attenuator at the ultraviolet end of the spectral range, but it also provided better maximum attenuation. The prisms were selected so that one crossed pair would have an attenuation equal to or greater than  $10^6:1$ . The prisms had a wavelength range of approximately 350 to 2500 nm and a tolerance on maximum beam deviation of approximately 6 arc sec.

The prisms were each mounted in precision stages. Two of the stages, manufactured by Klinger Scientific, Garden City, New York, were electronically driven. The first stage was required to accurately return to the 0-deg position and to have a repeatable 90-deg rotation. These criteria were easily met with one of the Klinger stages. The requirements for the second stage (middle polarizer) were the most stringent since this stage was the only one which would rotate after the attenuator was aligned. This stage was responsible for determining the angle " $\theta$ " with great accuracy. Consequently, the second stage consisted of a Klinger Scientific, Garden City, New York, stage and an encoder. The encoder on the middle stage was accurate to approximately 1 arc sec. The third stage was a manual stage which incorporated both fine and coarse adjustments. Figures 1a, 1b, and 1c show the assembled three-stage polarizer attenuator taken from the top (Fig. 1a), from the front (Fig. 1b), and from the side (Fig. 1c).



(a). Top view.

Figure 1. Three-stage polarizer attenuator.





(b). Side view.



(c). Front view.

Figure 1. Concluded.

## **2.2 ALIGNMENT OF THE ATTENUATOR**

The alignment for the stages was accomplished mechanically by using an optical post which was the same diameter as the prisms. The post was inserted through the mounts (where the prisms would be mounted) and then the mounts were adjusted and tightened down. The post was removed.

Each prism was then individually mounted in each stage position and tested. A target was placed 6 to 8 ft away from the attenuator and then the stage was rotated through 360 deg to ensure that the laser spot remained in the same location on the target. All three prisms performed properly.

An alignment procedure was developed which ensured the first and third polarizers had their optic axes in parallel positions and the second polarizer reached a minimum transmittance when it was crossed with the other two polarizers. The procedures used are described below and depicted in Figure 2. (Note: Prism 1 is mounted closest to the laser source, prism 2 is mounted in the center of the attenuator, and prism 3 is mounted closest to the detector.)

Step 1. Set all of the mounts to their 0-deg position and insert all the prisms in the same approximate orientation.

Step 2. Set prism 3 near the 90-deg or null position.

Step 3. Set prism 2 so that prisms 1 and 2 are exactly 90 deg off (cross polarized). This location should provide an exact null and prism 2 will be in approximately the 90-deg position.

Step 4. Set prism 1 in the same position as prism 2.

Step 5. Return prism 3 to the 0-deg position and adjust it until an exact null is reached (prisms 2 and 3 are crossed polarizers). Lock prism 3 in place.

Step 6. Return prism 1 to its exact original position. At this point, prisms 1 and 2 should be exactly 90 deg offset and prisms 2 and 3 should also be exactly 90 deg offset.

Step 7. Return prism 2 to its 0-deg position. The attenuator should now be set for maximum transmission.

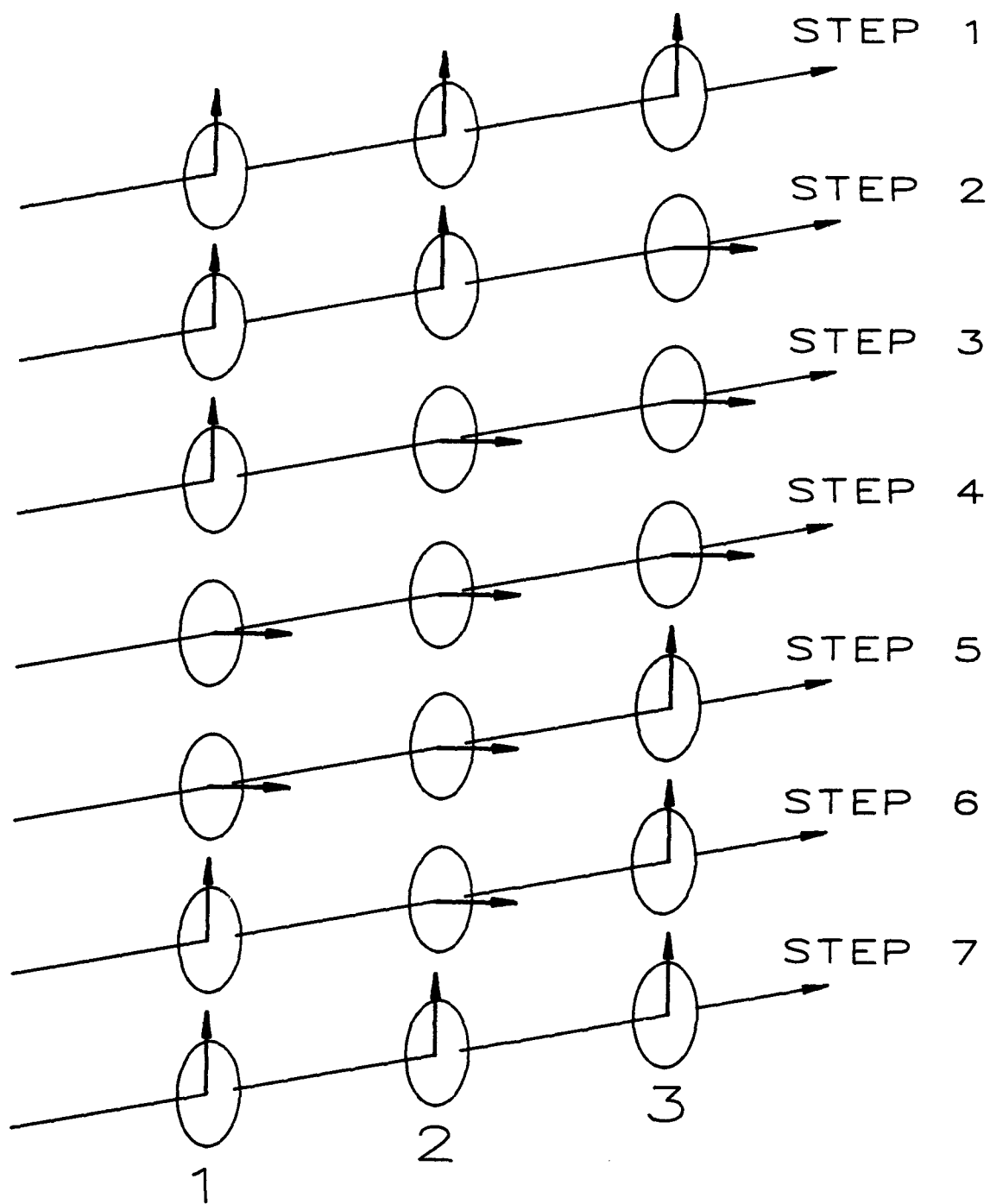


Figure 2. Attenuation alignment procedures.

## 2.3 EXPERIMENTAL LAYOUT

The three-stage attenuator was then tested in an experimental setup to determine its range and accuracy. The experimental schematic is shown in Figure 3.

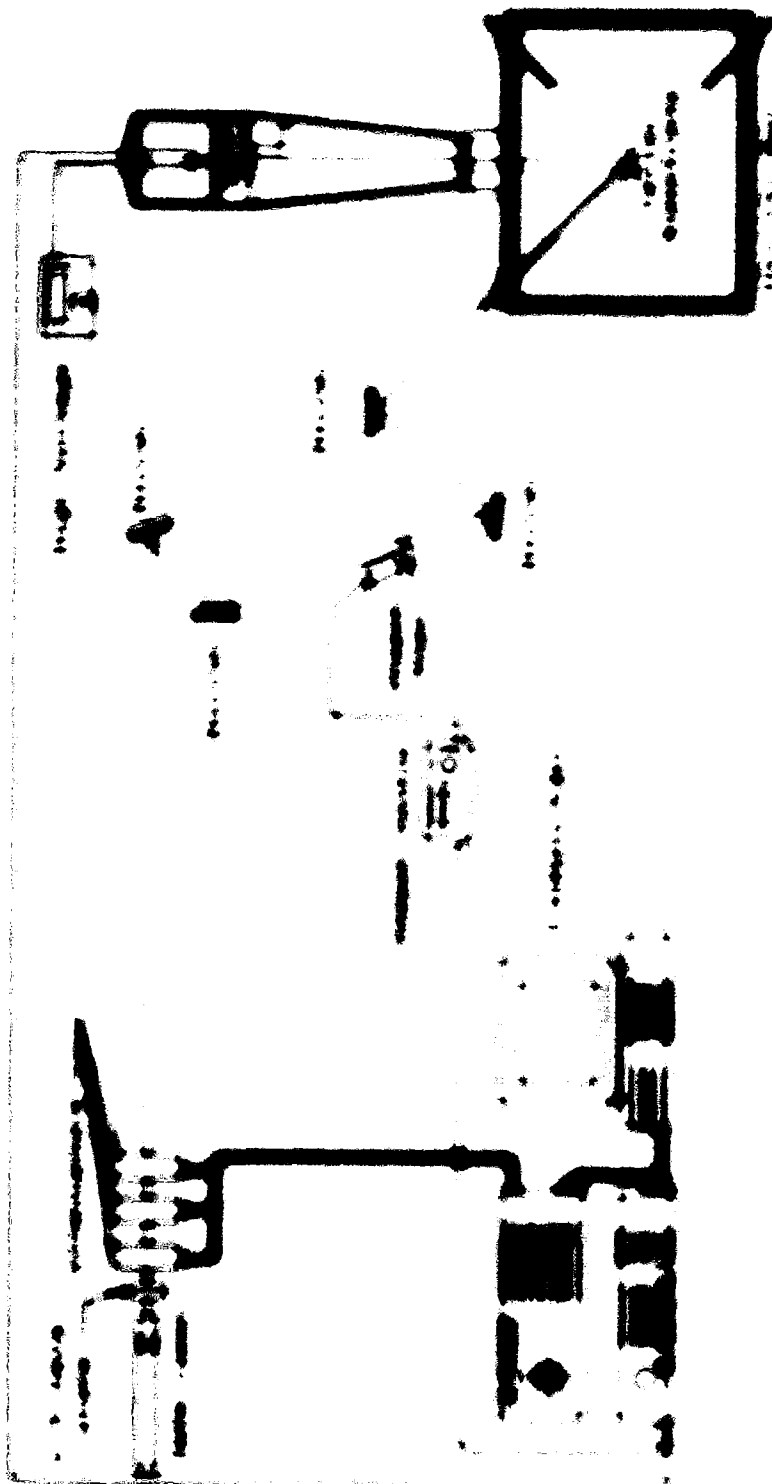
The laser was a 5-mW helium-neon laser (633 nm) with an adjustable beam expander. A quarter-wave plate was positioned between the beam expander and the attenuator. Consequently, a monochromatic, collimated, unpolarized light source was normally incident upon the attenuator. A series of mirrors were used to properly position the light for the detector.

A chopper with reflective blades was used to modulate part of the laser beam. The modulated beam was directed into an integrating sphere which was coupled to a silicon photodiode. The photodiode was connected to an input laser signal and was read on the lock-in amplifier.

The laser light then entered a utility box (measuring 31 x 31 x 15 cm) which was painted black in its walls for both the incident and reflected laser light. The box was designed to prevent the laser light from reflecting off the walls and causing the laser light to scatter. In this case a perfectly reflecting sphere was used as a reflector (Labsphere, Inc., North Sutton, Mass.) which was positioned at the center of the box. The laser beam entered the box at a 45 degree angle to the normal of the sample's normal. A portion of the reflected beam was directed towards the photometer. For alignment purposes, a third hole was drilled in the box so that the beam could exit when no sample was in place. Light from the laser was directed into the inner wall, were inserted through the small holes in the box. The light was directed towards the beam entered and exited the box. Alignment of the laser was done by observing the laser beam was adjusted until it appeared to be centered within the box. The tubes. Figure 4 illustrates the basic setup of the utility box.

The photometer, filter wheel assembly, and photomultiplier tube (PMT) were used to measure several capabilities: (1) the ability to scramble the signal stream in the detector, (2) the ability to focus the beam, (3) the ability to change aperture diameter, (4) the ability to eliminate most sources of stray light, and (5) the ability to reduce background noise. Neutral density filters in the optical train where the light rays were directed to the PMT axis. Figure 5 provides a ray diagram of the setup. The PMT was housed in a lead housing (Products for Research, Inc., Danvers, Mass.) which provided radiofrequency shielding, a double window and a dry air purge system for the reduction of dark current.

The PMT was connected to a phase lock amplifier. The gain of the amplifier was used to obtain data over a six order of magnitude dynamic range. Data over six orders of magnitude were obtained by attenuating the high end of the dynamic range with a National Institute of Science and Technology calibration grade optical density filter. Consequently, even the weak signals were above the detection limit of the PMT and within the linear range of the photomultiplier.





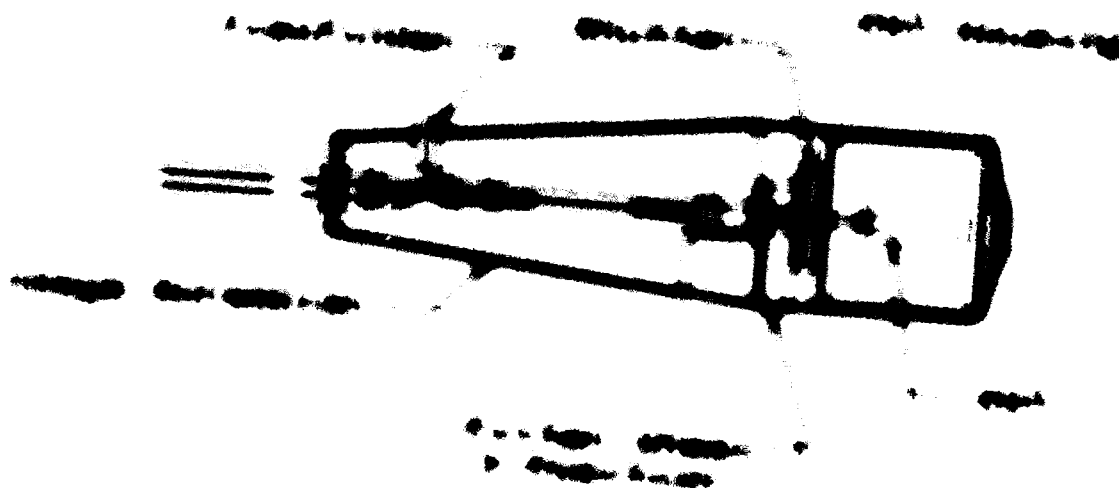


Figure 1: The diagram of the mechanical assembly shown in the figure.

## 1.1 DATA REPRESENTATION AND EXPERIMENTAL RESULTS

### 1.1.1 EXPERIMENTAL RESULTS

Figure 1 shows the experimental and theoretical curves plotted against the given values of  $\alpha$  and  $\beta$ . The theoretical curves were calculated at  $\alpha = 0.1$  and  $\beta = 0.1$ . The experimental curves were obtained at  $\alpha = 0.1$  and  $\beta = 0.1$ . The experimental curves are in good agreement with the theoretical curves.

Figure 2 shows the experimental and theoretical curves plotted against the given values of  $\alpha$  and  $\beta$ . The theoretical curves were calculated at  $\alpha = 0.1$  and  $\beta = 0.1$ . The experimental curves were obtained at  $\alpha = 0.1$  and  $\beta = 0.1$ . The experimental curves are in good agreement with the theoretical curves.

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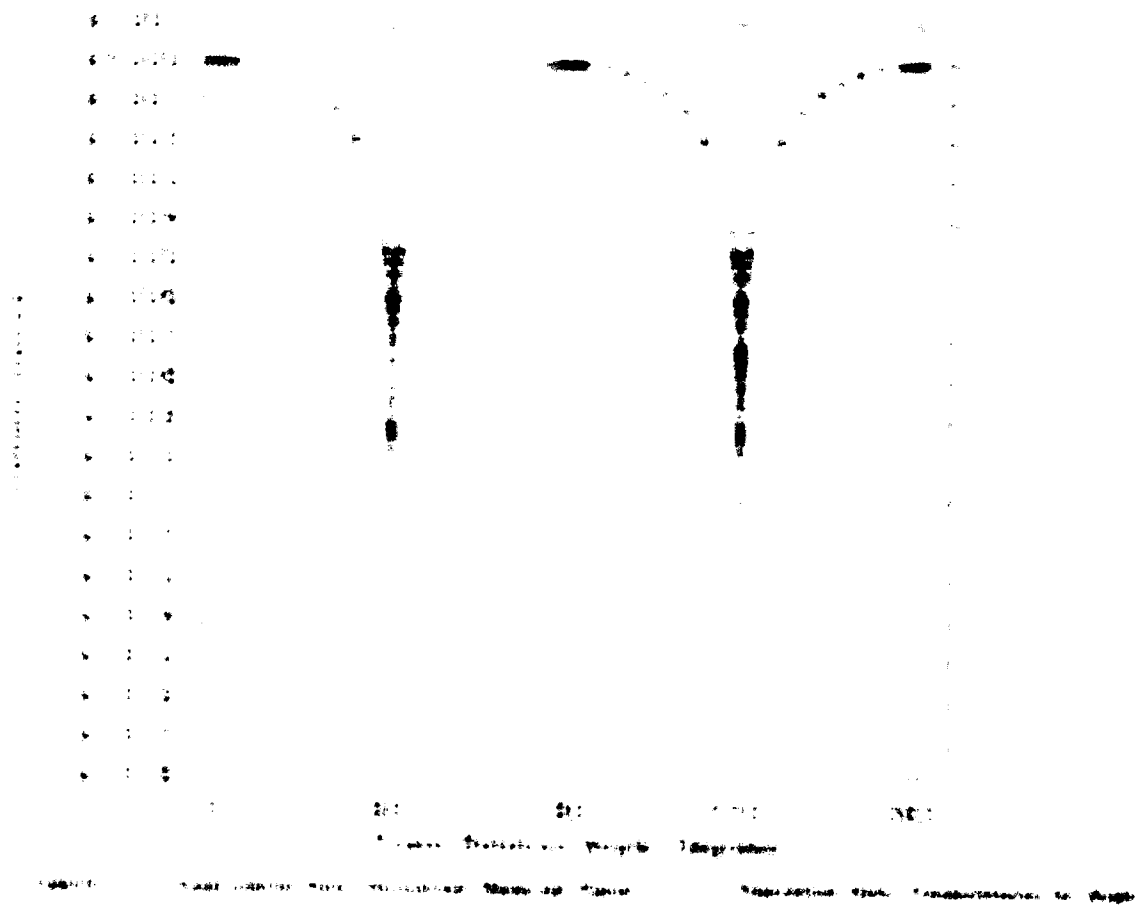


Figure 2. Experimental and theoretical curves for the first radial angle.

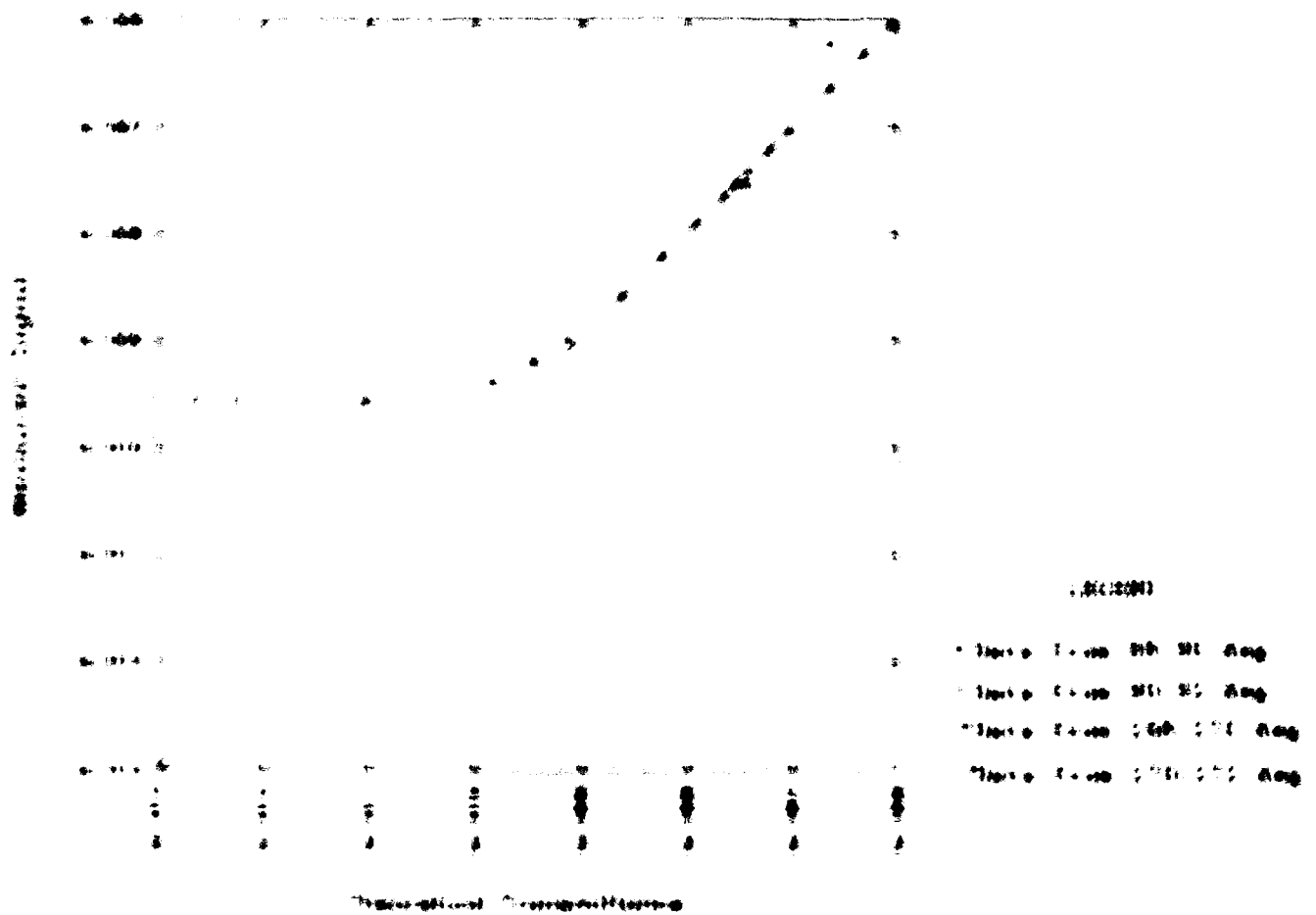
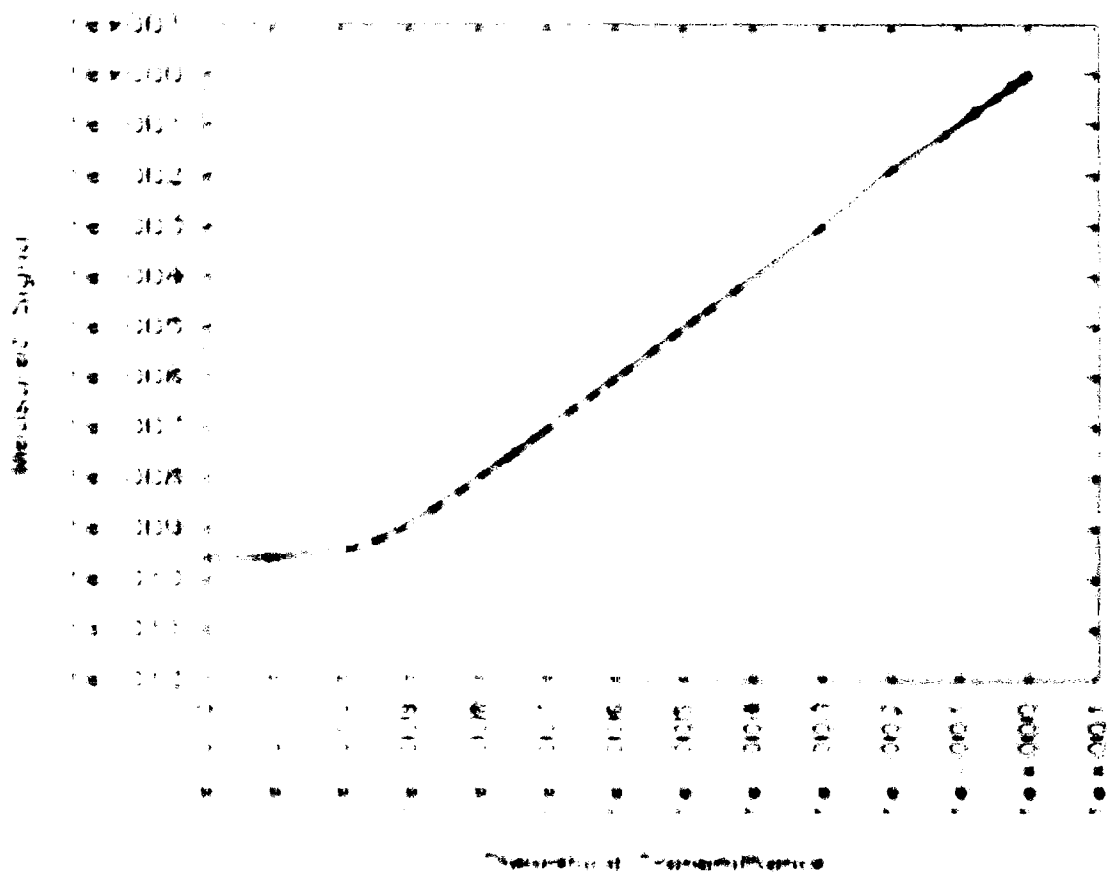
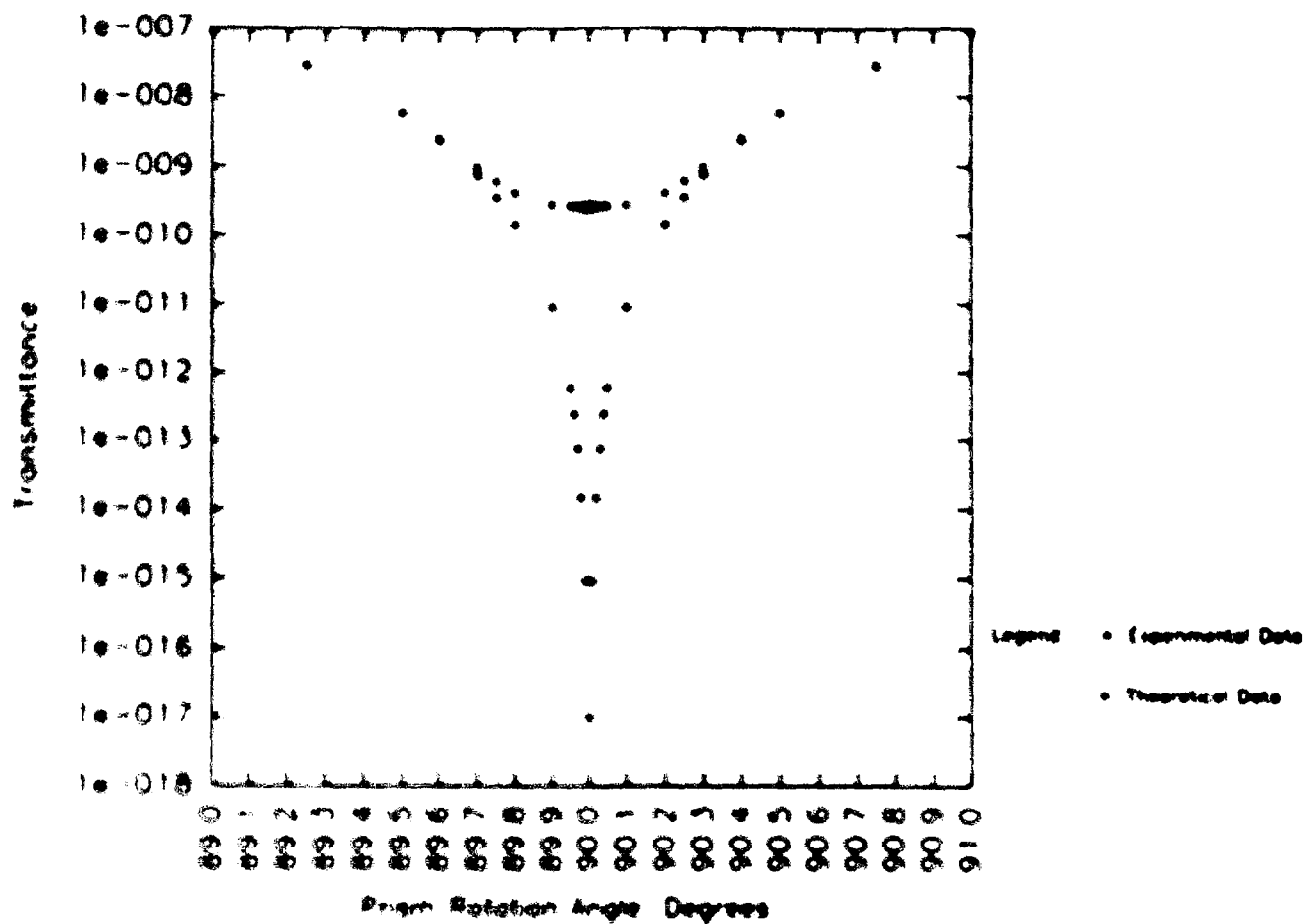


Figure 1. Observed signal strength versus theoretical signal strength for data in the vicinity of 100 and 100 dB.

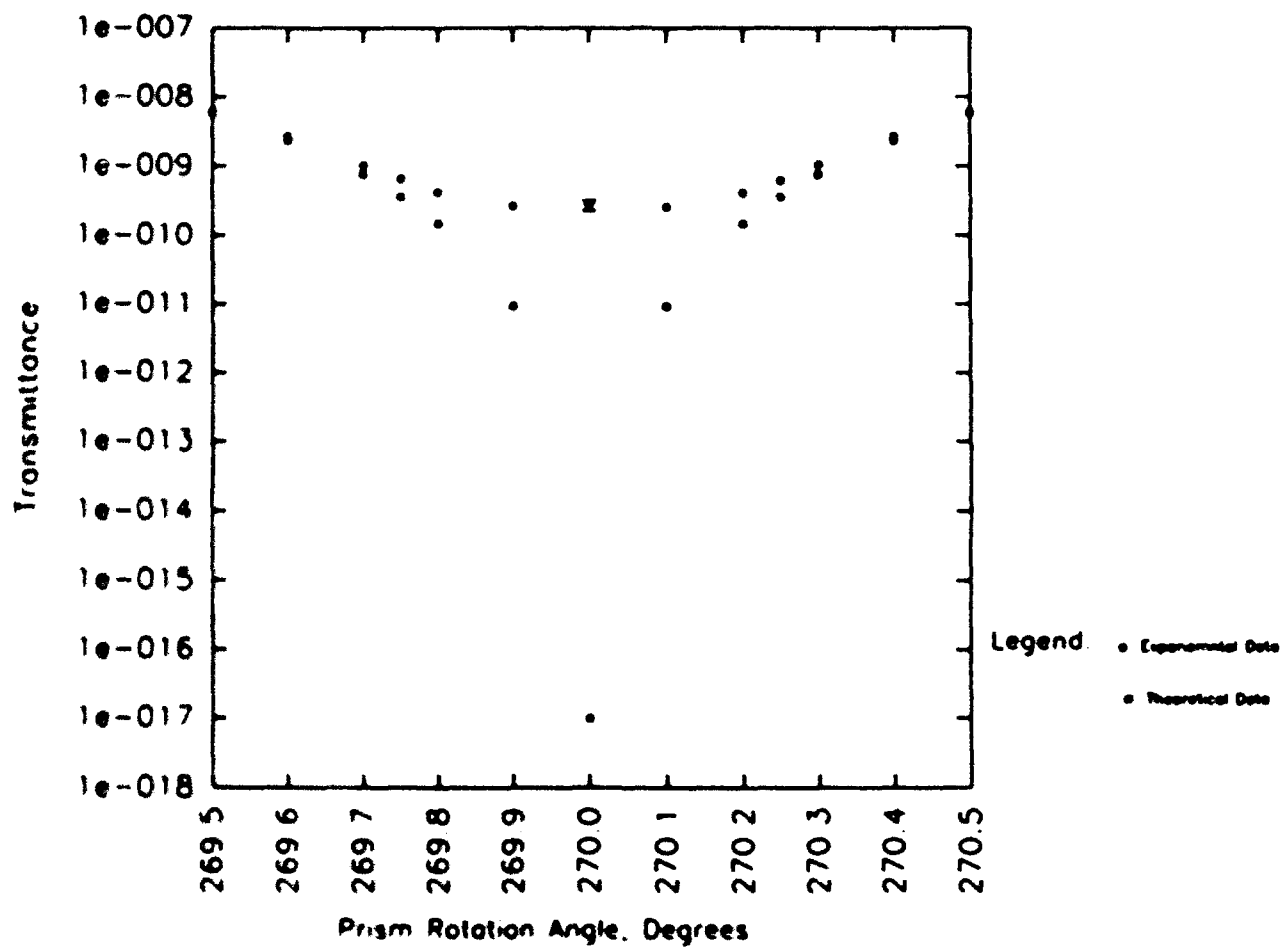


**Figure 2. Measured signal versus theoretical transmittance for the entire data set**



(a) Angles near 90-deg

Figure 9 Data plot of the transmittance versus the prism rotation angle.



(b) Angles near 270 deg.

Figure 9. Concluded.

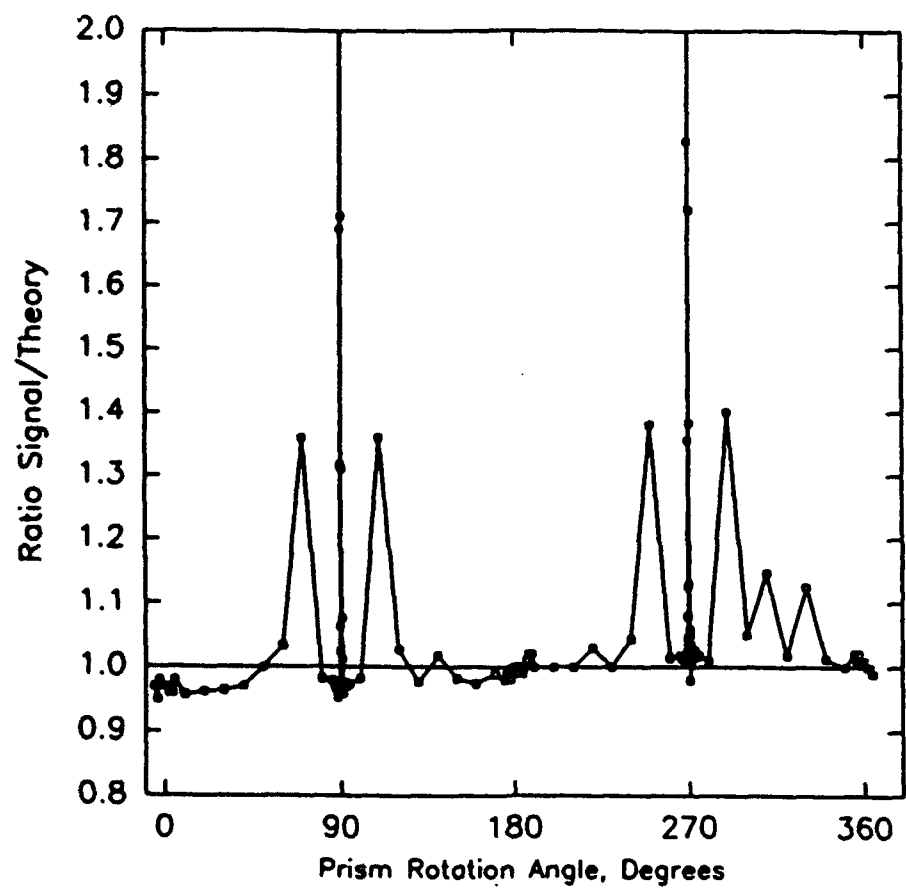


Figure 10. Ratio of the experimental transmittance to the theoretical transmittance versus the prism rotation angle.

## **3.2 EXPERIMENTAL ERROR**

### **3.2.1 Measurement Error**

There were several sources of measurement and random error present throughout the experiment. These errors include nonlinearity in the phase lock amplifier, noise from the photomultiplier, stray light in the optical train, variation in the lock-in amplifier reading, and drift in laser power. No attempt was made to control the laser power.

### **3.2.2 Systematic Error**

Data collected around the 0-, 90-, 180-, and 270-deg angles indicated significant systematic errors. The major errors include drift in the laser signal from the beginning to the end of the data run and slight alignment errors in the prisms. The drift was noticed in the signal from the beginning to the end of the data runs. In addition, the equipment was left for several 30-min intervals without altering the equipment setting and experimental data did change slightly with time. Alignment errors are noticed in the lack of perfect symmetry in data around the 0- and 360-deg points. In addition, there was a small double hump pattern around the 90- and 270-deg points. Additional systematic errors would include the temperature change in the room affecting the laser detector or the electronics and small inaccuracies in the mechanized center stage.

#### 4.0 CONCLUSIONS

The three-stage polarizer attenuator, with the advanced Glan-Thompson optical prisms, the extremely precise automated stages, and an experimental setup which allowed accurate measurements of high extinction ratios, was capable of providing attenuation of a laser beam for nine orders of magnitude with uncertainties of 1 to 2 percent. This attenuator was useful in providing practical accuracies of a few percent over a wide dynamic range with a simple technique. The data were symmetric throughout all four quadrants. The attenuator can be used to calibrate neutral density filters over a wavelength range from 350 to 2500 nm and over an optical density range of nine orders of magnitude. These results were obtained with laser sources only, and no corrections were made for drift in the laser power or signal processing.



## REFERENCES

1. Mielenz, K. D. and Echerle, K. L., "Accuracy of Polarization Attenuators," Applied Optics, Vol. 11, No. 3, pp. 594-603, March 1972.
2. Dowell, J. H., J Sci Instrum, Vol. 8, p. 382, 1931.
3. Bennett, H.E., "Accurate Method for Determining Photometric Linearity," Applied Optics, Vol. 5, No. 8, August 1966.

**APPENDIX A**  
**RAW DATA COLLECTION**

FILTER WHEEL POSITION	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000
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DATE	TIME	LOCATION	WIND	TEMP	MOON
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99	10	10	10	10	10
100	10	10	10	10	10

1941年 1月1日 1941年1月1日	1941年 1月1日 1941年1月1日	1941年 1月1日 1941年1月1日	1941年 1月1日 1941年1月1日	1941年 1月1日 1941年1月1日	1941年 1月1日 1941年1月1日
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72	72	72	72	72	72



FILTER WHEEL POSITION	0	LOCK-IN READING	FILTER WHEEL POSITION	0	LOCK-IN READING
1	66.50	$1.252 \pm 1.0000$ 1	3	176.00	$2.75 \pm$ $0.005 \text{ v}$
1	68.00	$1.700 \pm 1.0000$ 1	3	176.00	$2.75 \pm$ $0.005 \text{ v}$
1	69.50	$1.25 \pm 1.0000$ 1	3	180.00	$2.75 \pm$ $0.005 \text{ v}$
1	80.00	$2.25 \pm 1.0000$ 1	3	181.00	$2.75 \pm$ $0.005 \text{ v}$
1	80.00	$100 \pm 1.00 \mu\text{A}$	3	182.00	$2.75 \pm 0.005 \text{ v}$
1	80.00	$1000 \pm 1.0 \mu\text{A}$	3	185.00	$2.75 \pm$ $0.005 \text{ v}$
1	100.00	$2.00 \pm$ $1.0000 \text{ v}$	3	186.00	$2.75 \pm$ $0.005 \text{ v}$
1	110.00	$27.0 \pm 1.00 \text{ v}$	3	188.00	$2.00 \pm$ $0.005 \text{ v}$
1	120.00	$100 \pm 1.0 \text{ v}$	3	188.00	$2.00 \pm$ $0.005 \text{ v}$
1	130.00	$1.000 \pm$ $1.0000 \text{ v}$	3	190.00	$2.10 \pm$ $0.005 \text{ v}$
1	140.00	$1.400 \pm 1.0000$ 1	3	191.00	$1.50 \pm$ $0.005 \text{ v}$
1	150.00	$1.05 \pm 1.0000$ 1	3	192.00	$0.000 \pm$ $0.0000 \text{ v}$
1	160.00	$0.37 \pm 1.0000$ 1	3	193.00	$0.675 \pm$ $0.0000 \text{ v}$
1	170.00	$0.20 \pm 1.0000$ 1	3	194.00	$0.175 \pm$ $0.0000 \text{ v}$
1	170.00	$0.05 \pm 1.0000$ 1	3	195.00	$0.0 \pm$ $0.0000 \text{ v}$
1	170.00	$0.00 \pm$ $1.0000 \text{ v}$	3	196.00	$0.50 \pm$ $0.0000 \text{ v}$
1	170.00	$0.00 \pm 1.0000$ 1	3	196.00	$0.100 \pm 0.0000 \text{ v}$



FILTER WHEEL POSITION	$\theta$ ( $^{\circ}$ )	LOCK-IN READING	FILTER WHEEL POSITION	$\theta$ ( $^{\circ}$ )	LOCK-IN READING
3	266.00	$67.2 \pm 0.3 \mu\text{V}$	1	266.90	$26.7 \pm 0.3 \mu\text{V}$
1	266.00	$2.41 \pm 0.005 \text{ V}$	1	270.00	$26.0 \pm 0.3 \mu\text{V}$
1	266.50	$1.42 \pm 0.005 \text{ V}$	1	270.10	$26.5 \pm 0.1 \mu\text{V}$
1	267.00	$0.705 \pm 0.0005 \text{ V}$	1	270.20	$41.4 \pm 0.05 \mu\text{V}$
1	267.50	$0.370 \pm 0.0005 \text{ V}$	1	270.30	$105.4 \pm 0.05 \mu\text{V}$
1	268.00	$15.1 \pm 0.5 \text{ mV}$	1	270.40	$272 \pm 0.5 \mu\text{V}$
1	268.25	$60.0 \pm 0.05 \text{ mV}$	1	270.50	$0.632 \pm 0.0005 \text{ mV}$
1	268.50	$48.3 \pm 0.05 \text{ mV}$	1	270.60	$1.20 \pm 0.005 \text{ mV}$
1	268.75	$0.50 \pm 0.005 \text{ mV}$	1	270.70	$2.33 \pm 0.005 \text{ mV}$
1	268.90	$0.35 \pm 0.005 \text{ mV}$	1	270.80	$2.87 \pm 0.005 \text{ mV}$
1	269.20	$3.02 \pm 0.005 \text{ mV}$	1	270.90	$0.36 \pm 0.005 \text{ mV}$
1	269.30	$2.37 \pm 0.005 \text{ mV}$	1	271.00	$0.57 \pm 0.005 \text{ mV}$
1	269.40	$1.25 \pm 0.005 \text{ mV}$	1	271.10	$48.5 \pm 0.05 \text{ mV}$
1	269.50	$0.002 \pm 0.0005 \text{ mV}$	1	271.20	$80.1 \pm 0.05 \text{ mV}$
1	269.60	$271 \pm 0.5 \mu\text{V}$	1	271.30	$152 \pm 0.5 \text{ mV}$
1	269.70	$132 \pm 0.5 \mu\text{V}$	1	271.50	$0.272 \pm 0.0005 \text{ V}$
1	269.80	$42.1 \pm 0.5 \mu\text{V}$	1	271.60	$0.700 \pm 0.0005 \text{ V}$

FILTER WHEEL POSITION	$\theta$ ( $^{\circ}$ )	LOCK-IN READING	FILTER WHEEL POSITION	$\theta$ ( $^{\circ}$ )	LOCK-IN READING
1	273.50	$1.42 \pm 0.005$ V	3	360.00	$2.78 \pm 0.005$ V
1	274.00	$2.41 \pm 0.005$ V	3	361.00	$2.76 \pm 0.005$ V
3	274.00	$66.9 \pm 0.05$ $\mu$ V	3	362.00	$2.75 \pm 0.005$ V
3	275.00	$163 \pm 0.5$ $\mu$ V	3	363.00	$2.73 \pm 0.005$ V
3	280.00	$2.48 \pm 0.005$ mV	3	364.00	$2.71 \pm 0.005$ V
3	290.00	$38.0 \pm 0.05$ mV	3	365.00	$2.70 \pm 0.005$ V
3	300.00	$171 \pm 0.5$ mV	3	0.00	$2.78 \pm 0.005$ V
3	310.00	$0.488 \pm 0.0005$ V	3	1.00	$2.76 \pm 0.005$ V
3	320.00	$0.862 \pm 0.0005$ V	3	2.00	$2.73 \pm 0.005$ V
3	330.00	$1.56 \pm 0.005$ V	3	3.00	$2.71 \pm 0.005$ V
3	340.00	$2.20 \pm 0.005$ V	3	-1.00	$2.77 \pm 0.005$ V
3	350.00	$2.59 \pm 0.005$ V	3	-2.00	$2.78 \pm 0.005$ V
3	355.00	$2.77 \pm 0.005$ V	3	-3.00	$2.77 \pm 0.005$ V
3	360.00	$2.79 \pm 0.005$ V	3	0.00	$2.68 \pm 0.005$ V
3	367.00	$2.79 \pm 0.005$ V	1	88.50	$0.599 \pm 0.0005$ mV
3	368.00	$2.79 \pm 0.005$ V	1	88.80	$256 \pm 0.5$ $\mu$ V
3	369.00	$2.79 \pm 0.005$ V	1	89.70	$100 \pm 0.5$ $\mu$ V

FILTER WHEEL POSITION	$\theta$ (°)	LOCK-IN READING	FILTER WHEEL POSITION	$\theta$ (°)	LOCK-IN READING
1	89.80	$42.2 \pm 0.05 \mu\text{V}$	1	90.500	$0.591 \pm 0.0005 \text{ mV}$
1	89.90	$29.3 \pm 0.05 \mu\text{V}$			
1	89.95	$28.0 \pm 0.05 \mu\text{V}$			
1	89.96	$27.8 \pm 0.05 \mu\text{V}$			
1	89.97	$27.6 \pm 0.05 \mu\text{V}$			
1	89.98	$27.7 \pm 0.05 \mu\text{V}$			
1	89.99	$28.1 \pm 0.05 \mu\text{V}$			
1	90.00	$28.3 \pm 0.05 \mu\text{V}$			
1	90.01	$28.0 \pm 0.05 \mu\text{V}$			
1	90.02	$27.8 \pm 0.05 \mu\text{V}$			
1	90.03	$27.8 \pm 0.05 \mu\text{V}$			
1	90.04	$27.7 \pm 0.05 \mu\text{V}$			
1	90.05	$27.5 \pm 0.05 \mu\text{V}$			
1	90.100	$28.7 \pm 0.05 \mu\text{V}$			
1	90.200	$42.8 \pm 0.05 \mu\text{V}$			
1	90.300	$99.8 \pm 0.05 \mu\text{V}$			
1	90.400	$259 \pm 0.5 \mu\text{V}$			

**APPENDIX B**  
**REDUCED DATA**

$\theta$	TRANSMITTANCE $\cos^4 \theta$	EXPERIMENTAL VALUE	NORMALIZED EXPERIMENTAL VALUE
-5.00	0.98	$2.62\text{E}00 \pm 0.01$	0.95E00
-4.00	0.99	$2.61\text{E}00 \pm 0.01$	0.94E00
-3.00	0.99	$2.69\text{E}00 \pm 0.09$	0.97E00
-2.00	1.00	$2.70\text{E}00 \pm 0.09$	0.97E00
-1.00	1.00	$2.70\text{E}00 \pm 0.08$	0.97E00
0.00	1.00	$2.70\text{E}00 \pm 0.11$	0.97E00
1.00	1.00	$2.69\text{E}00 \pm 0.07$	0.97E00
2.00	1.00	$2.68\text{E}00 \pm 0.06$	0.96E00
3.00	0.99	$2.67\text{E}00 \pm 0.04$	0.96E00
4.00	0.99	$2.63\text{E}00 \pm 0.01$	0.95E00
5.00	0.98	$2.67\text{E}00 \pm 0.01$	0.96E00
10.00	0.94	$2.51\text{E}00 \pm 0.07$	0.90E00
20.00	0.78	$2.08\text{E}00 \pm 0.02$	0.75E00
30.00	0.56	$1.51\text{E}00 \pm 0.05$	0.54E00
40.00	0.34	$0.92\text{E}00 \pm 0.02$	0.33E00
50.00	0.17	$0.47\text{E}00 \pm 0.02$	0.17E00
60.00	0.06	$1.72\text{E}-01 \pm 0.05\text{E}-01$	0.62E-01
70.00	0.01	$3.77\text{E}-02 \pm 0.08\text{E}-02$	1.36E-02
80.00	9.09E-04	$2.48\text{E}-03 \pm 0.07\text{E}-03$	8.93E-04
85.00	5.77E-05	$1.57\text{E}-04 \pm 0.06\text{E}-04$	5.65E-05
86.00	2.37E-05	$6.44\text{E}-05 \pm 0.2\text{E}-05$	2.32E-05
86.50	1.39E-05	$3.75\text{E}-05 \pm 0.04\text{E}-05$	1.35E-05
87.00	7.5E-06	$2.02\text{E}-05 \pm 0.03\text{E}-05$	7.27E-06
87.50	3.62E-06	$9.67\text{E}-06 \pm 0.16\text{E}-06$	3.48E-06
88.00	1.48E-06	$3.93\text{E}-06 \pm 0.03\text{E}-06$	1.41E-06
88.25	8.70E-07	$2.32\text{E}-06 \pm 0.01\text{E}-06$	8.35E-07
88.50	4.70E-07	$1.26\text{E}-06 \pm 0.01\text{E}-07$	4.54E-07

$\theta$	TRANSMITTANCE $\cos^4 \theta$	EXPERIMENTAL VALUE	NORMALIZED EXPERIMENTAL VALUE
88.75	2.26E-07	$6.06\text{E-}07 \pm 0.04\text{E-}07$	2.18E-07
89.00	9.28E-08	$2.50\text{E-}07 \pm 0.03\text{E-}07$	9.00E-08
89.25	2.94E-08	$7.98\text{E-}08 \pm 0.14\text{E-}08$	2.87E-08
89.50	5.80E-09	$1.65\text{E-}08 \pm 0.06\text{E-}08$	5.94E-09
89.60	2.38E-09	$7.04\text{E-}09 \pm 0.02\text{E-}09$	2.53E-09
89.70	7.52E-10	$2.75\text{E-}09 \pm 0.02\text{E-}09$	9.90E-10
89.75	3.62E-10	$1.70\text{E-}09 \pm 0.03\text{E-}09$	6.12E-10
89.80	1.48E-10	$1.16\text{E-}09 \pm 0.03\text{E-}09$	4.18E-10
89.90	9.28E-12	$8.06\text{E-}10 \pm 0.03\text{E-}10$	2.90E-10
89.95	5.80E-13	$7.70\text{E-}10 \pm 0.01\text{E-}10$	2.77E-10
89.96	2.38E-13	$7.65\text{E-}10 \pm 0.01\text{E-}10$	2.75E-10
89.97	7.52E-14	$7.59\text{E-}10 \pm 0.01\text{E-}10$	2.73E-10
89.98	1.48E-14	$7.62\text{E-}10 \pm 0.01\text{E-}10$	2.74E-10
89.99	9.28E-16	$7.73\text{E-}10 \pm 0.01\text{E-}10$	2.78E-10
90.00	0	$7.60\text{E-}10 \pm 0.45\text{E-}10$	2.74E-10
90.01	9.28E-16	$7.70\text{E-}10 \pm 0.01\text{E-}10$	2.77E-10
90.02	1.48E-14	$7.65\text{E-}10 \pm 0.01\text{E-}10$	2.75E-10
90.03	7.52E-14	$7.65\text{E-}10 \pm 0.01\text{E-}10$	2.75E-10
90.04	2.38E-13	$7.62\text{E-}10 \pm 0.01\text{E-}10$	2.74E-10
90.05	5.80E-13	$7.56\text{E-}10 \pm 0.01\text{E-}10$	2.72E-10
90.10	9.28E-12	$7.89\text{E-}10 \pm 0.01\text{E-}10$	2.84E-10
90.20	1.48E-10	$1.17\text{E-}09 \pm 0.01\text{E-}09$	4.21E-10
90.25	3.62E-10	$1.72\text{E-}09 \pm 0.06\text{E-}09$	6.19E-10
90.30	7.52E-10	$2.74\text{E-}09 \pm 0.01\text{E-}09$	9.86E-10
90.40	2.38E-09	$7.12\text{E-}09 \pm 0.01\text{E-}09$	2.56E-09
90.50	5.80E-09	$1.63\text{E-}08 \pm 0.01\text{E-}08$	5.87E-09
90.75	2.94E-08	$7.84\text{E-}08 \pm 0.05\text{E-}08$	2.82E-08

$\theta$	TRANSMITTANCE $\cos^4 \theta$	EXPERIMENTAL VALUE	NORMALIZED EXPERIMENTAL VALUE
91.00	9.28E-08	$2.49\text{E-}07 \pm 0.02\text{E-}07$	8.96E-08
91.25	2.26E-07	$6.08\text{E-}07 \pm 0.03\text{E-}07$	2.19E-07
91.50	4.70E-07	$1.27\text{E-}06 \pm 0.01\text{E-}07$	4.57E-07
91.75	8.70E-07	$2.36\text{E-}06 \pm 0.04\text{E-}07$	8.50E-07
92.00	1.48E-06	$3.99\text{E-}06 \pm 0.03\text{E-}06$	1.44E-06
92.50	3.62E-06	$9.75\text{E-}06 \pm 0.07\text{E-}06$	3.51E-06
93.00	7.50E-06	$2.02\text{E-}05 \pm 0.01\text{E-}05$	7.27E-06
93.50	1.39E-05	$3.74\text{E-}05 \pm 0.03\text{E-}05$	1.35E-05
94.00	2.37E-05	$6.41\text{E-}05 \pm 0.01\text{E-}05$	2.31E-05
95.00	5.77E-05	$1.56\text{E-}04 \pm 0.01\text{E-}04$	5.62E-05
100.00	9.09E-04	$2.48\text{E-}03 \pm 0.02\text{E-}03$	8.93E-04
110.00	0.01	$3.78\text{E-}02 \pm 0.05\text{E-}02$	1.36E-02
120.00	0.06	$1.71\text{E-}01 \pm 0.03\text{E-}01$	6.16E-02
130.00	0.17	$0.46\text{E}00 \pm 0.07\text{E-}01$	1.66E-01
140.00	0.34	$0.96\text{E}00 \pm 0.02\text{E}00$	3.46E-01
150.00	0.56	$1.53\text{E}00 \pm 0.01\text{E}00$	0.55E00
160.00	0.78	$2.12\text{E}00 \pm 0.05\text{E}00$	0.76E00
170.00	0.94	$2.59\text{E}00 \pm 0.06\text{E}00$	0.93E00
175.00	0.98	$2.68\text{E}00 \pm 0.06\text{E}00$	0.96E00
176.00	0.99	$2.71\text{E}00 \pm 0.03\text{E}00$	0.98E00
177.00	0.99	$2.72\text{E}00 \pm 0.01\text{E}00$	0.98E00
178.00	1.00	$2.73\text{E}00 \pm 0.05\text{E-}01$	0.98E00
179.00	1.00	$2.75\text{E}00 \pm 0.01\text{E}00$	0.99E00
180.00	1.00	$2.77\text{E}00 \pm 0.03\text{E}00$	1.00E00
181.00	1.00	$2.76\text{E}00 \pm 0.01\text{E}00$	0.99E00
182.00	1.00	$2.75\text{E}00 \pm 0.01\text{E}00$	0.99E00
183.00	0.99	$2.74\text{E}00 \pm 0.03\text{E}00$	0.99E00

$\theta$	TRANSMITTANCE $\cos^4 \theta$	EXPERIMENTAL VALUE	
184.00	0.99	$2.73E-03 \pm 1.14E-03$	
185.00	0.98	$2.73E-03 \pm 1.14E-03$	
186.00	0.98	$2.70E-03 \pm 1.11E-03$	
187.00	0.97	$2.74E-03 \pm 1.11E-03$	
188.00	0.96	$2.72E-03 \pm 1.11E-03$	
189.00	0.95	$2.69E-03 \pm 1.11E-03$	
190.00	0.94	$2.61E-03 \pm 1.10E-03$	
200.00	0.78	$2.14E-03 \pm 1.11E-03$	
210.00	0.56	$1.54E-03 \pm 1.03E-03$	
220.00	0.34	$0.94E-03 \pm 1.17E-03$	
230.00	0.17	$0.48E-03 \pm 1.11E-03$	
240.00	0.06	$1.74E-04 \pm 1.12E-03$	
250.00	0.01	$3.84E-05 \pm 1.10E-03$	
260.00	$9.09E-04$	$2.54E-03 \pm 1.11E-03$	
265.00	$5.77E-05$	$1.43E-04 \pm 1.12E-03$	
266.00	$2.37E-05$	$6.88E-05 \pm 1.10E-03$	
266.50	$1.39E-05$	$2.91E-05 \pm 1.10E-03$	
267.00	$7.50E-06$	$2.11E-05 \pm 1.11E-03$	
267.50	$3.62E-06$	$1.07E-05 \pm 1.11E-03$	
268.00	$1.48E-06$	$4.15E-06 \pm 1.11E-03$	
268.25	$8.70E-07$	$2.48E-06 \pm 1.10E-03$	
268.50	$4.70E-07$	$1.32E-06 \pm 1.10E-03$	
268.75	$2.26E-07$	$6.41E-07 \pm 1.11E-03$	
269.00	$9.28E-08$	$2.84E-07 \pm 1.10E-03$	
269.10	$6.09E-08$	$1.72E-07 \pm 1.11E-03$	
269.20	$3.80E-08$	$1.08E-07 \pm 1.11E-03$	
269.25	$2.94E-08$	$8.52E-08 \pm 1.11E-03$	



$\theta$	TRANSMITTANCE COEF $\theta$	EXPERIMENTAL VALUE	CALCULATED EXPERIMENTAL VALUE
260.30	2.22E-08	6.88E-08 $\pm$ 1.17E-08	6.88E-08
260.40	1.20E-08	3.04E-08 $\pm$ 1.17E-08	3.04E-08
260.50	5.80E-08	7.40E-08 $\pm$ 1.10E-08	7.40E-08
260.60	2.20E-08	7.02E-08 $\pm$ 1.17E-08	7.02E-08
260.70	7.52E-11	2.65E-08 $\pm$ 1.17E-08	2.65E-08
260.75	3.82E-11	7.04E-08 $\pm$ 1.17E-08	7.04E-11
260.80	1.00E-11	7.40E-08 $\pm$ 1.17E-08	7.40E-11
260.85	9.20E-12	7.04E-11 $\pm$ 1.17E-11	7.04E-11
270.00	1	7.04E-11 $\pm$ 1.00E-11	7.04E-11
270.10	8.20E-12	7.04E-11 $\pm$ 1.17E-11	7.04E-11
270.20	1.00E-11	7.40E-08 $\pm$ 1.17E-08	7.40E-11
270.25	3.82E-11	7.40E-08 $\pm$ 1.17E-08	7.40E-11
270.30	7.52E-11	6.88E-08 $\pm$ 1.17E-08	6.88E-08
270.40	2.20E-08	7.02E-08 $\pm$ 1.17E-08	7.02E-08
270.50	5.80E-08	7.40E-08 $\pm$ 1.10E-08	7.40E-08
270.60	1.20E-08	3.04E-08 $\pm$ 1.17E-08	3.04E-08
270.70	6.20E-08	6.88E-08 $\pm$ 1.17E-08	6.88E-08
270.75	6.20E-08	6.88E-08 $\pm$ 1.17E-08	6.88E-08
270.80	3.82E-08	7.04E-08 $\pm$ 1.17E-08	7.04E-08
270.90	9.20E-08	7.04E-08 $\pm$ 1.17E-08	7.04E-08
271.00	3.82E-08	6.88E-08 $\pm$ 1.17E-08	6.88E-08
271.20	6.20E-08	6.88E-08 $\pm$ 1.17E-08	6.88E-08
271.30	9.20E-08	7.04E-08 $\pm$ 1.17E-08	7.04E-08
271.40	9.20E-08	7.04E-08 $\pm$ 1.17E-08	7.04E-08
272.00	1.00E-08	6.88E-08 $\pm$ 1.17E-08	6.88E-08
272.50	3.82E-08	7.04E-08 $\pm$ 1.17E-08	7.04E-08
273.00	1.00E-08	6.88E-08 $\pm$ 1.17E-08	6.88E-08

PREFACE		CONTENTS		APPENDIX		INDEX	
PAGE		PAGE		PAGE		PAGE	
1	1	1	1	1	1	1	1
2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3
4	4	4	4	4	4	4	4
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15	15	15	15	15	15	15	15
16	16	16	16	16	16	16	16
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26	26	26	26	26	26	26	26
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29	29	29	29	29	29	29	29
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37	37	37	37	37	37	37	37
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42	42	42	42	42	42	42	42
43	43	43	43	43	43	43	43
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45	45	45	45	45	45	45	45
46	46	46	46	46	46	46	46
47	47	47	47	47	47	47	47
48	48	48	48	48	48	48	48
49	49	49	49	49	49	49	49
50	50	50	50	50	50	50	50

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